

The future of California's climate from a global perspective

William D. Collins

UC Berkeley and Lawrence Berkeley Lab

Acknowledgements: Julie Arblaster and Claudia Tebaldi

IPCC results: The IPCC WG1 bureau and fellow authors

- The global context of regional climate change
 - *Recent changes in global temperature and sea level*
 - *Attribution of these changes to human causes*
 - *Global warming during the 21st century*
- Climate change in the western regional US
- Changes in climatic extremes in the western US
 - *What are climate extremes?*
 - *Projections for temperature and precipitation extremes*
- Future developments in global climate projections

Findings from the new IPCC report



The Intergovernmental Panel on Climate Change (IPCC) was set up jointly by the World Meteorological Organization and the United Nations Environment Programme to provide an authoritative international assessment of scientific understanding of climate change. The IPCC's periodic assessments of the causes, impacts and possible response strategies to climate change are the most comprehensive and up-to-date reports available on the subject, and form the standard reference for all concerned with climate change in academia, government and industry worldwide. Through three working groups, many hundreds of international experts assess climate change in this Fourth Assessment Report. The Report consists of three main volumes under the umbrella title *Climate Change 2007*, all available from Cambridge University Press:

Climate Change 2007 - The Physical Science Basis

Contribution of Working Group I to the Fourth Assessment Report of the IPCC
(ISBN 978 0 521 88009 1 Hardcover, 978 0 521 70594 7 Paperback)

Climate Change 2007 - Impacts, Adaptation and Vulnerability

Contribution of Working Group II to the Fourth Assessment Report of the IPCC
(ISBN 978 0 521 88010 7 Hardcover, 978 0 521 70595 4 Paperback)

Climate Change 2007 - Mitigation of Climate Change

Contribution of Working Group III to the Fourth Assessment Report of the IPCC
(ISBN 978 0 521 88011 4 Hardcover, 978 0 521 70596 1 Paperback)

Climate Change 2007 - The Physical Science Basis is the most comprehensive and up-to-date scientific assessment of past, present and future climate change. The report provides:

- the most complete and quantitative assessment of how human activities are affecting the radiative energy balance in the atmosphere
- a more extensive assessment of changes observed throughout the climate system than ever before using the latest measurements covering the atmosphere, land surface, oceans, and snow, ice and frozen ground
- a detailed assessment of past climate change and its causes
- the first probabilistic assessment of climate model simulations and projections using detailed atmosphere-ocean coupled models from 18 modelling centres around the world
- a detailed assessment of climate change observations, modelling, and attribution for every continent

Simply put, this latest assessment of the IPCC will again form the standard scientific reference for all those concerned with climate change and its consequences, including students and researchers in environmental science, meteorology, climatology, biology, ecology and atmospheric chemistry, and policy makers in governments and industry worldwide.

From reviews of the Third Assessment Report - Climate Change 2001:

'The detail is truly amazing... is valuable works of reference... no reference or science library should be without a set of the IPCC volumes... an extremely recommended to all readers.'
Journal of Meteorology

'This well-edited set of three volumes will surely be the standard reference for nearly all arguments related with global warming and climate change in the next years. It should not be missing in the libraries of atmospheric and climate research institutions and those administrative and political institutions which have to deal with global change and sustainable development.'
Metereologische Zeitschrift

'... likely to remain a vital reference work until further research renders the details outdated by the time of the next survey... another significant step forward in the understanding of the likely impacts of climate change on a global scale.'
International Journal of Climatology

'The IPCC has conducted what is arguably the largest, most comprehensive and transparent study ever undertaken by mankind... The result is a work of substance and authority, which only the British would deride.'
Wallpapering

'The subject is explored in great depth and should prove valuable to policy makers, researchers, students, and teachers.'
American Meteorological Society

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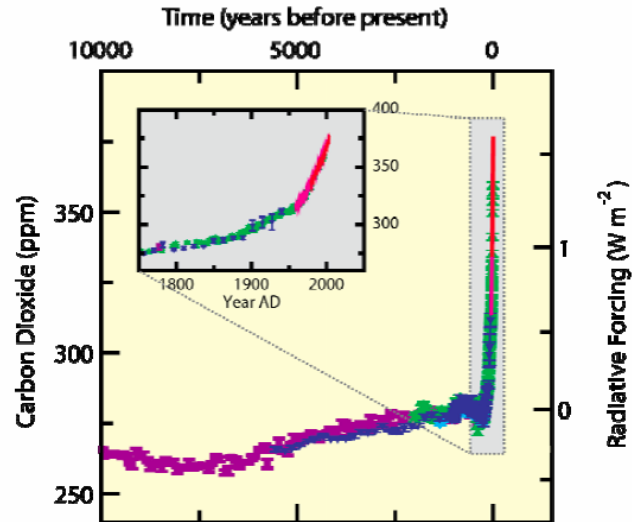
CLIMATE CHANGE 2007 THE PHYSICAL SCIENCE BASIS



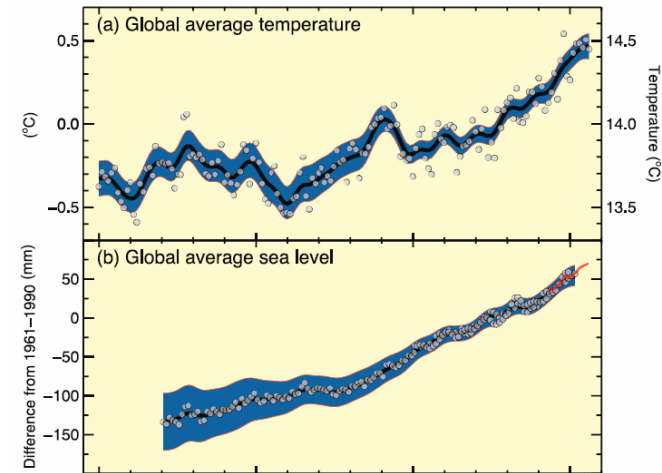
Working Group I Contribution to the Fourth Assessment
Report of the Intergovernmental Panel on Climate Change



Historical forcing and climate change



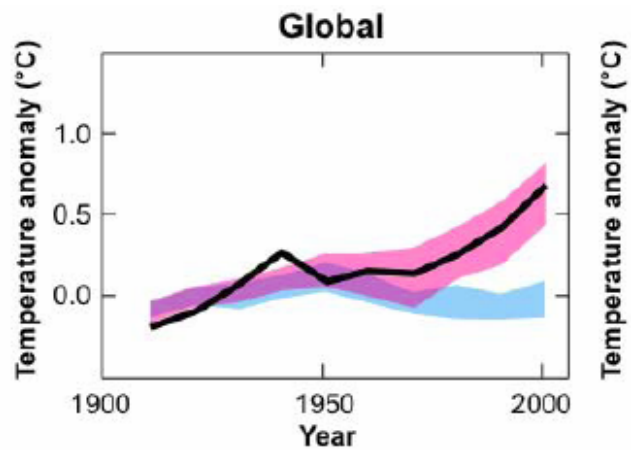
- *CO₂ was constant for almost 10000 years.*
- *CO₂ has risen rapidly in the industrial age.*



- *Temperatures have risen by 0.76K since 1850.*
- *Sea level has risen by roughly 1 foot since 1850.*

IPCC AR4, 2007

Attribution of past climate change



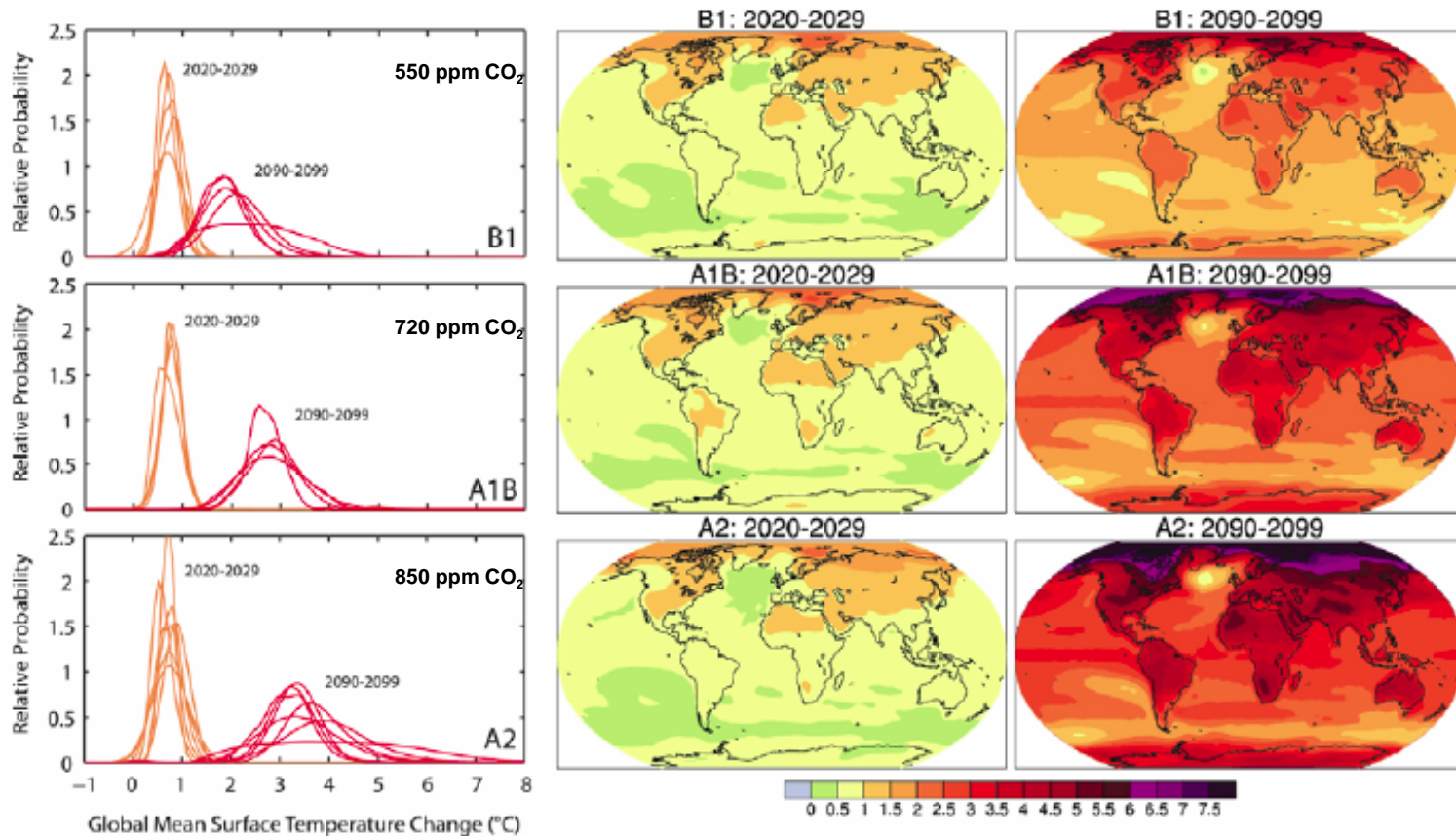
Observations and
models with all forcings
are shown in black and
pink respectively. The
pink shaded area is the
range of the models.

- Observations
- Models with all forcings
- Models with natural forcings

- Models with only natural forcings do not match observations.
- It is very likely (>90%) humans are cause of recent warming.

IPCC AR4, 2007

Climate change in the 21st century



- Warming by 2030 is scenario-invariant and is 2x natural variability.
- Warming by 2100 is scenario-dependent and ranges from 1.8 to 4C.

IPCC AR4, 2007

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Temperature projections for US



QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

- *Warming by 2100 in western North America is at least 2°C.*
- *Warming increases almost linearly with time.*

IPCC AR4, 2007

Regional temperature projections for 2100

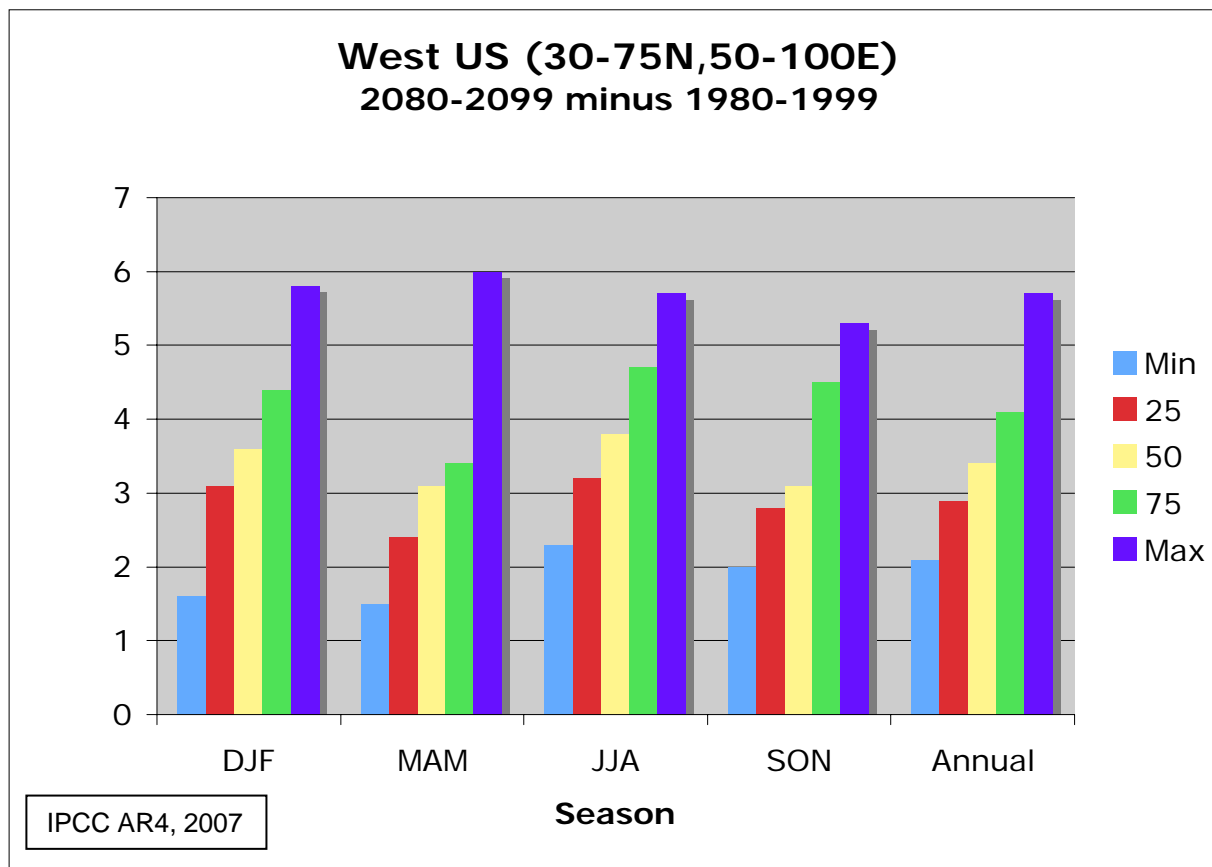


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- *Warming in western North America is largest during summer.*

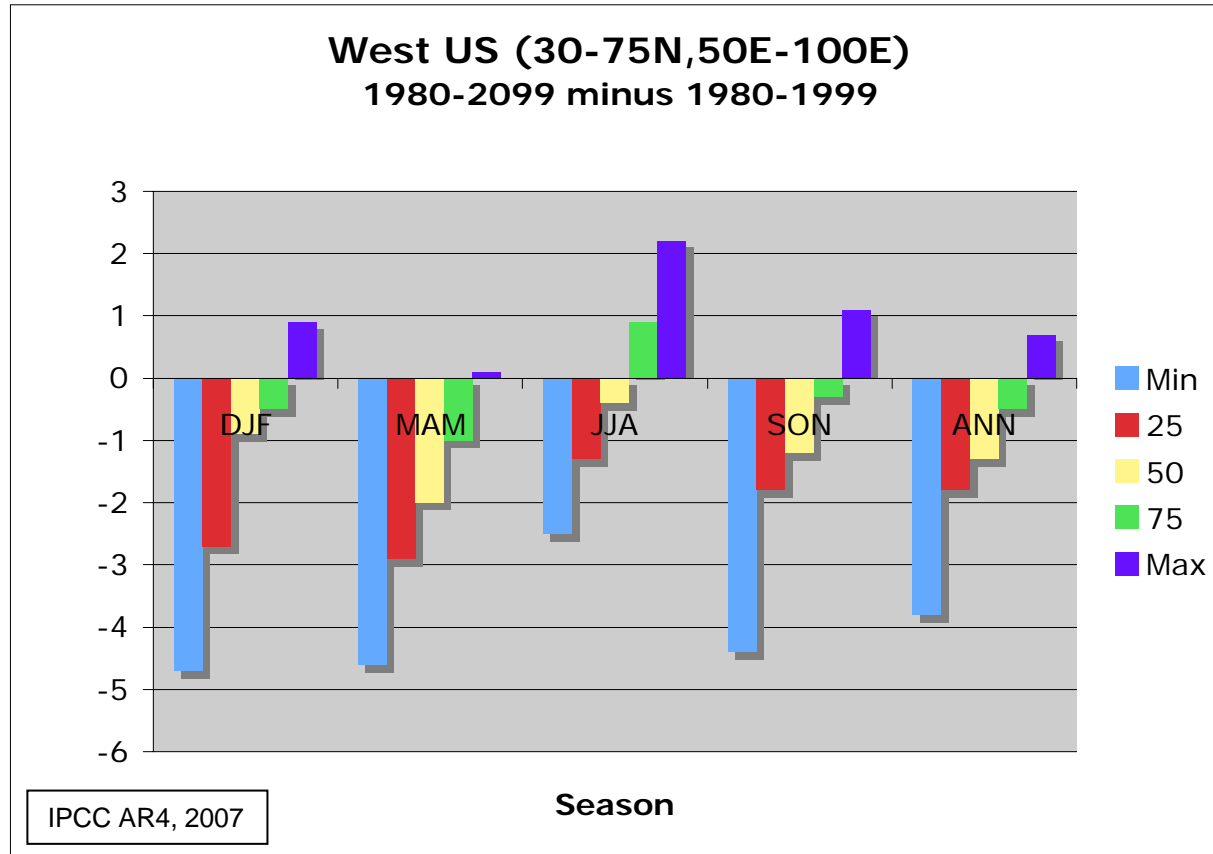
IPCC AR4, 2007

Range in temperature change among models



- *These signals will dominate natural variability after enough time.*
- *Time scale ranges from 10 years (summer) to 25 years (winter).*

Model fidelity for current climate



- *The fidelity of the model projections can be judged using model biases.*
- *The median model biases are much smaller than projected warming.*

Regional precipitation projections for 2100

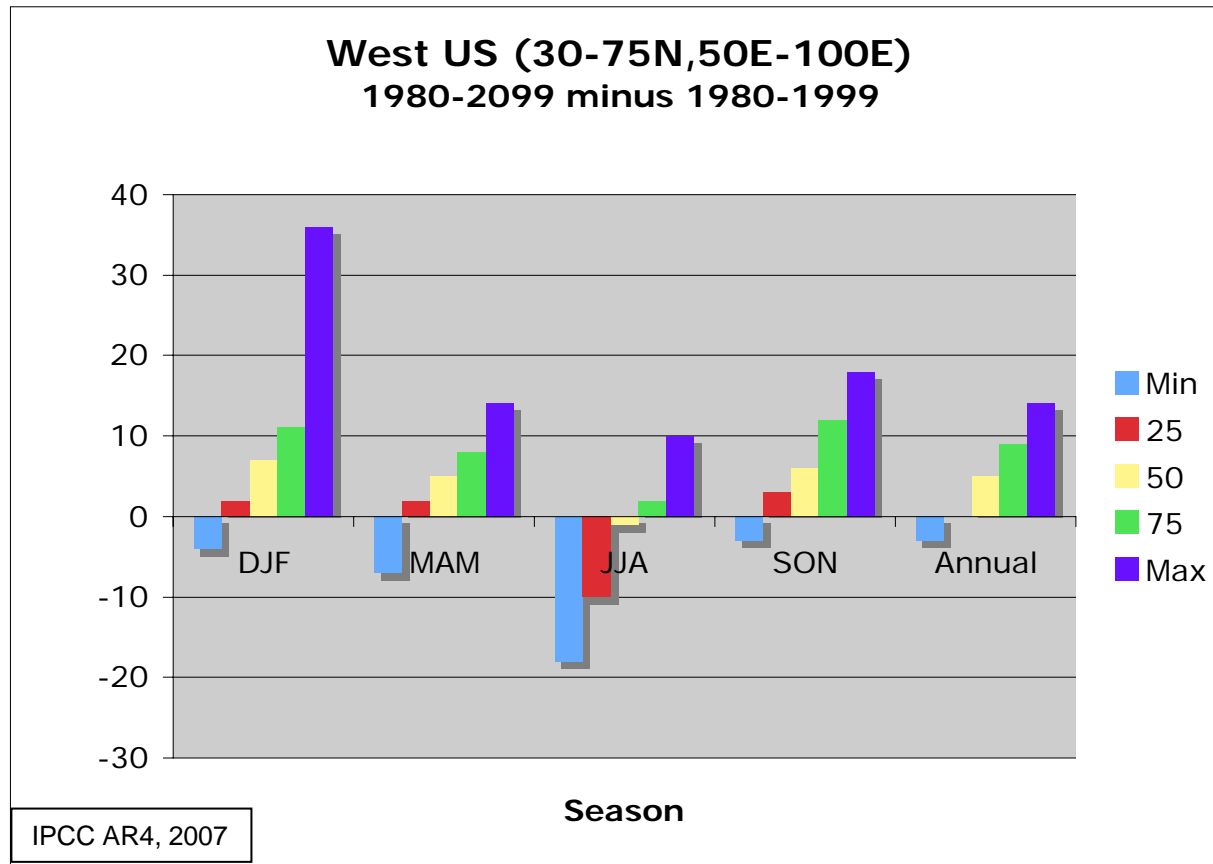


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- *Precipitation is displaced northward with the shifting storm tracks.*
- *Subpolar moistening and subtropical drying dominates the projections.*

Model range in precipitation

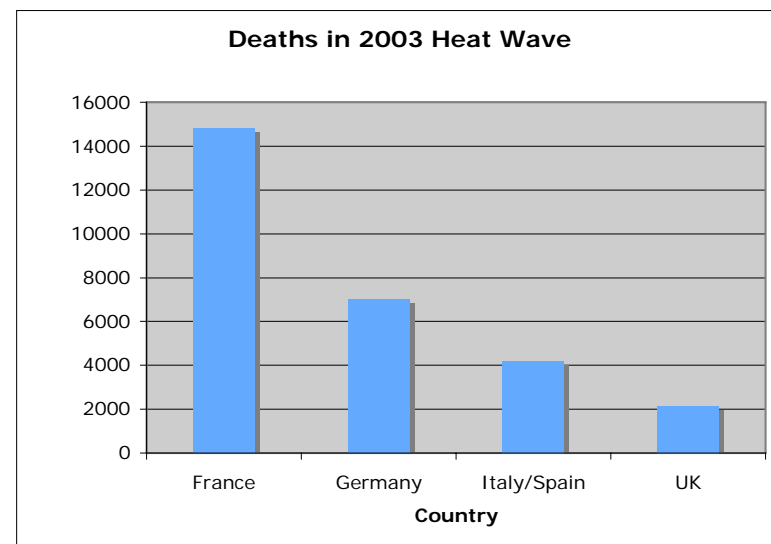
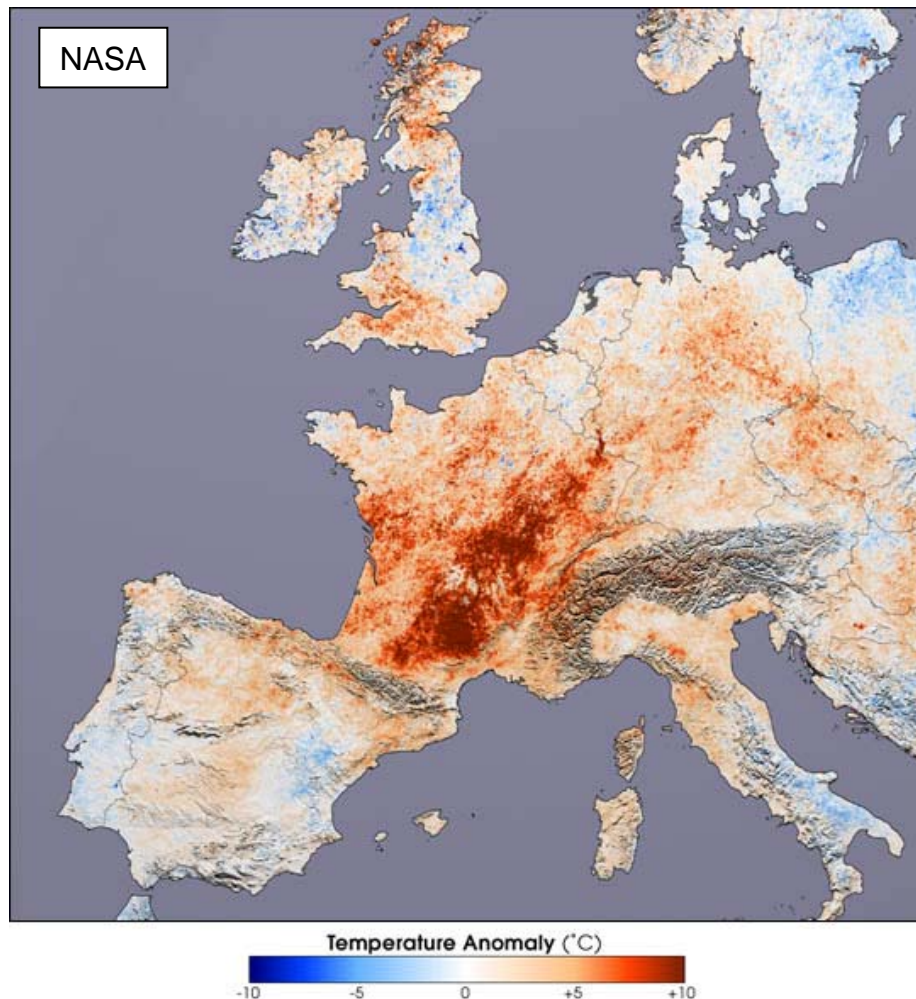


- *There is a weak trend toward greater precipitation over the western region.*
- *This trend becomes distinct from natural variability at >70 years.*

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Climate extremes: 2003 European heat wave

August 2003 temperature anomalies



What is a climate extreme?



Monthly average August 2003 temperatures

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are needed to see this picture.

IPCC AR4, 2007

An extreme is a climatologically unusual condition -
In the case of the European heat wave, high temperature.

Shifts in climatic “bell curve” can cause extremes



Summer daily maximum temperatures

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IPCC AR4, 2007

Extremes analysis (I)



- Objective:

Project regional changes in *climate extremes indices* for temperature and precipitation over the 21st century

- Climate extremes indices:

Measures of local change in extreme events such as heat waves, heavy rain or snow events, and droughts

- Selection of 10 indices of climate extremes:

- *These indices capture a wide spectrum of climate extreme characteristics.*
- *These indices are robust despite measurement and predictive uncertainty.*

- Source of projections:

Nine climate models used in the 4th IPCC assessment

Extremes analysis (II)



- Definition of the indices of climate extremes
- Sources of uncertainty in projections for these indices
- The models used to project these indices for 2000-2100
- The scenarios used for future emissions of greenhouse gases
- Schema for the regional projections
- Regional projections for *North America*

Climate extreme indices for temperature



- **Total number of frost days:**

Annual number of days with absolute minimum temperature below 0° C

- **Growing season length:**

Length of period between first and last 5 consecutive days with mean temperature above 5° C

- **Warm nights:**

Percentage of times in year when minimum temperature is above the 90th percentile of the climatological distribution for that calendar day

- **Intra-annual extreme temperature range:**

Difference between highest and lowest temperature of the year

- **Heat wave duration index:**

Maximum period of at least 5 consecutive days with maximum temperature higher by at least 5° C than the climatological norm

Climate extreme indices for precipitation



- **Simple daily intensity index:**

Annual total precipitation divided by number of wet days with rainfall greater than 1 mm

- **Maximum 5-day total precipitation**

- **Fraction of total precipitation from events exceeding 95th percentile**

- **Number of days with precipitation greater than 10 mm**

- **Maximum number of consecutive dry days:**

Rainfall less than 1 mm on each day

- **Uncertainty in future emissions:**
 - *Resolution: project changes for a wide range of emissions scenarios*

- **Uncertainty in the accuracy of projections from any single climate model:**
 - *Resolution: project changes using a wide variety of atmosphere-ocean general circulation models*

Models in multi-model ensemble

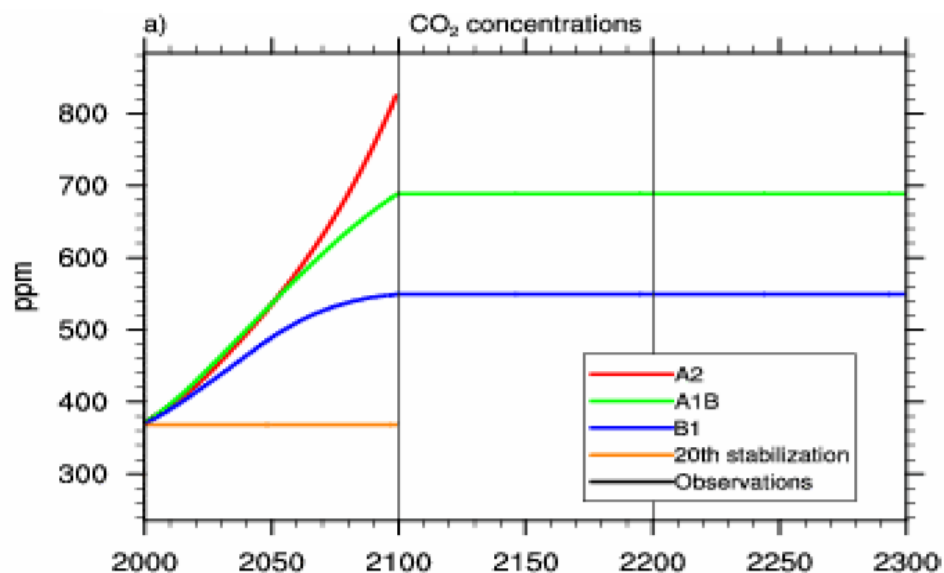


TABLE I
The nine Atmosphere-Ocean General Circulation Models featured in our analysis

Modeling center	AOGCM	Climate sensitivity (TCR)
National Center for Atmospheric Research (USA)	CCSM3	1.46
Météo-France & Centre National de Recherches Météorologiques (France)	CNRM-CM3	1.57
US Dept. of Commerce & National Oceanic and Atmospheric Administration & Geophysical Fluid Dynamics Laboratory (USA)	GFDL-CM2.0	1.60
US Dept. of Commerce & National Oceanic and Atmospheric Administration & Geophysical Fluid Dynamics Laboratory (USA)	GFDL-CM2.1	1.50
Institute for Numerical Mathematics (Russia)	INM-CM3	1.57
Center for Climate System Research & National Institute for Environmental Studies & Frontier Research Center for Global Change (JAPAN)	MIROC3.2(medres)	2.11
Center for Climate System Research & National Institute for Environmental Studies & Frontier Research Center for Global Change (JAPAN)	MIROC3.2(hires)	NA
Department of Energy & National Center for Atmospheric Research (USA)	PCM	1.32
Meteorological Research Institute & Japan Meteorological Agency (Japan)	MRI-CGCM2	0.97

Tebaldi et al, 2006

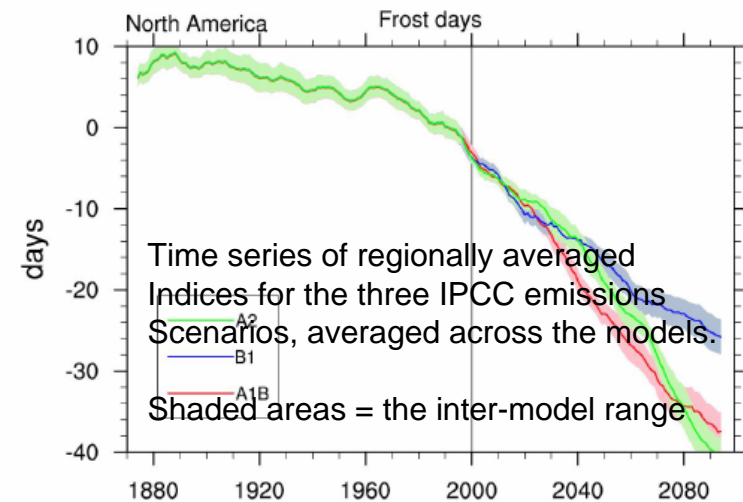
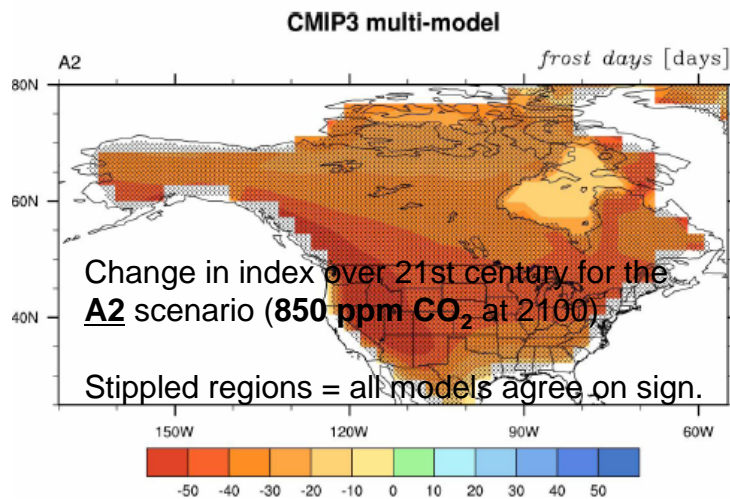
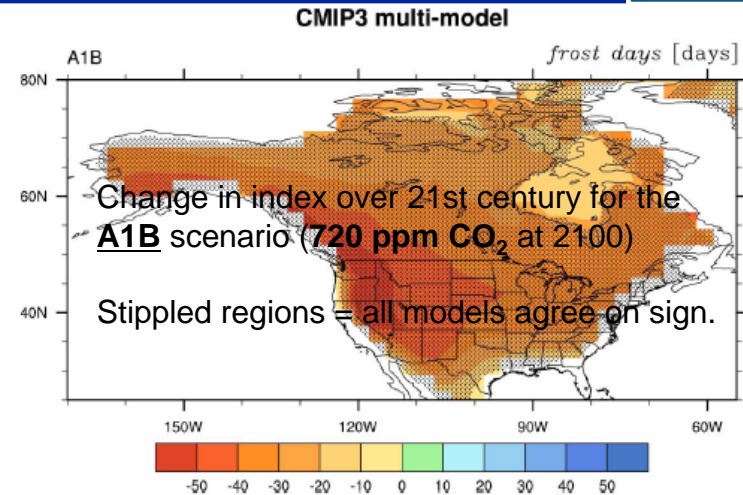
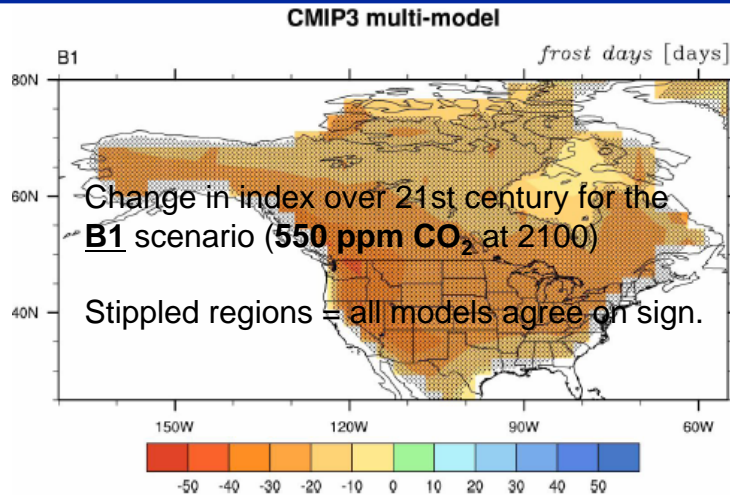
Scenarios for future emissions



IPCC emissions scenarios:

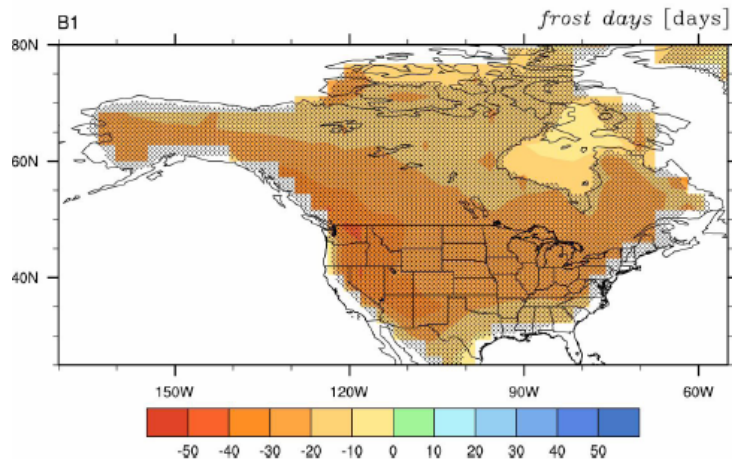
- A2:
A very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other scenarios.
- A1B:
A future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies.
- B1:
A convergent world with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.

Schema: Climate index maps & series

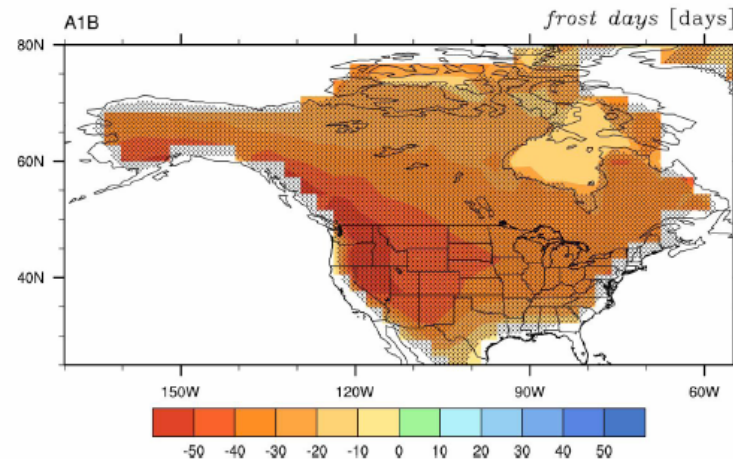


Number of frost days

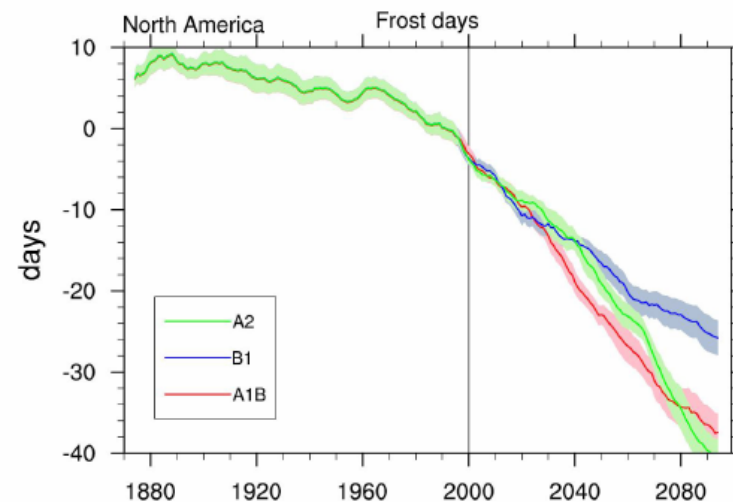
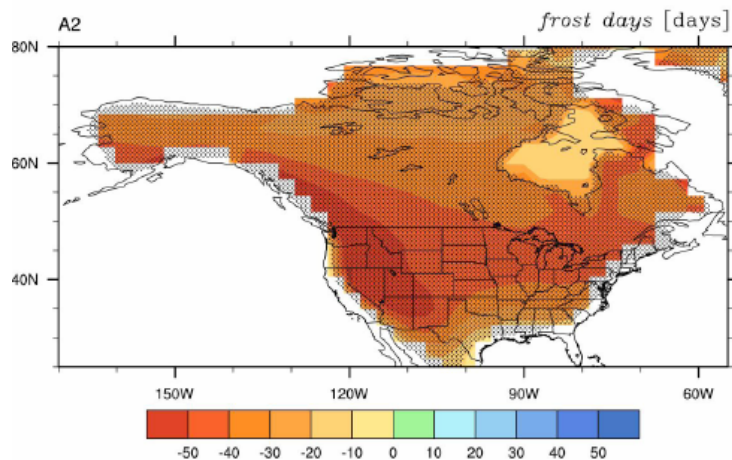
CMIP3 multi-model



CMIP3 multi-model

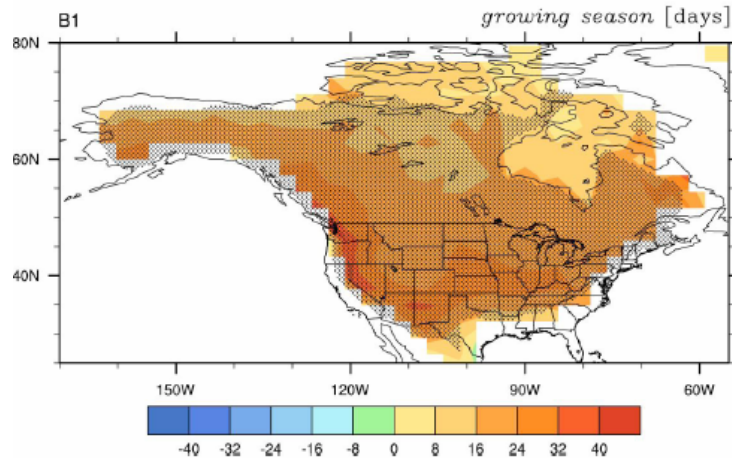


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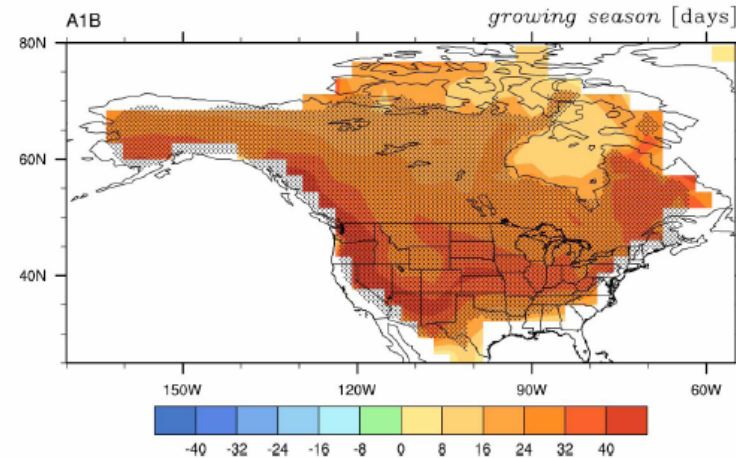


Growing season length

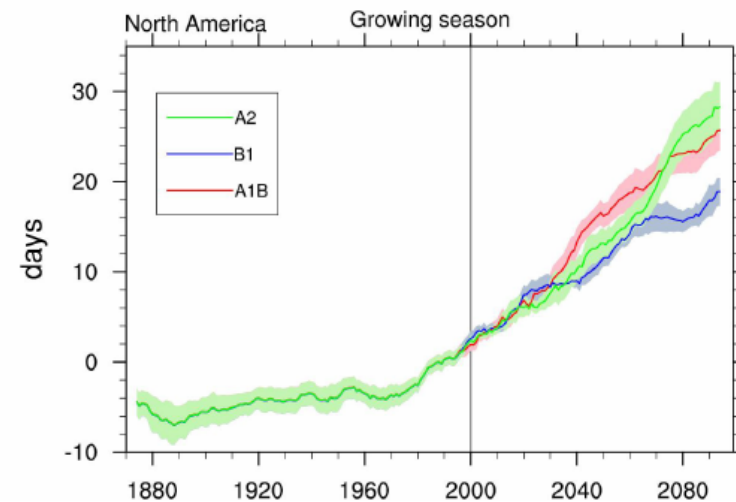
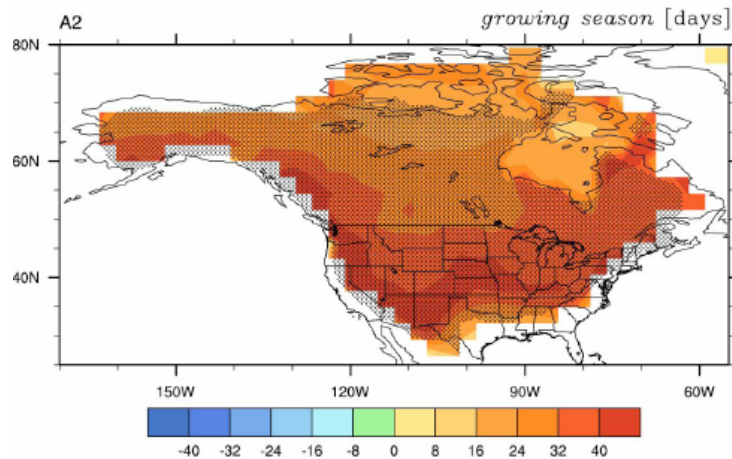
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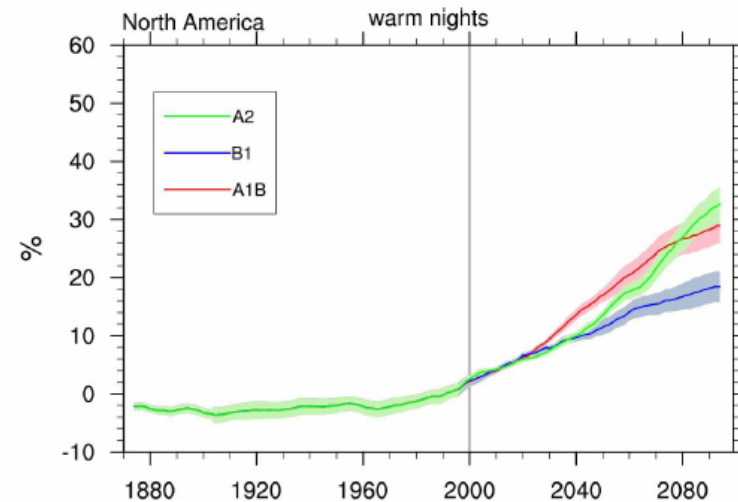
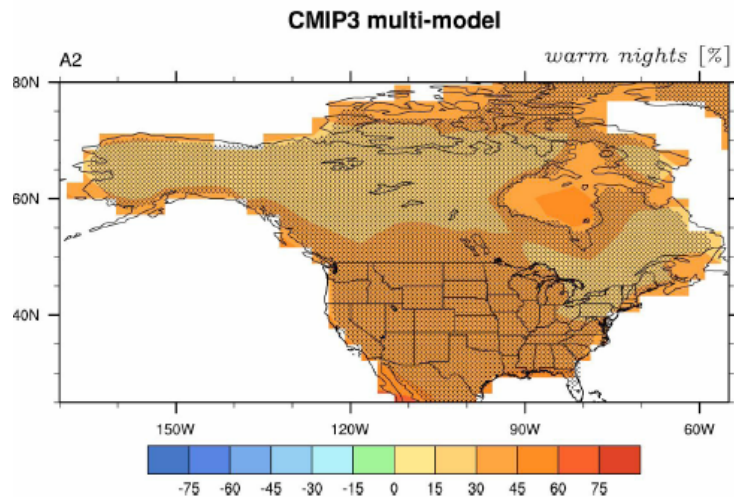
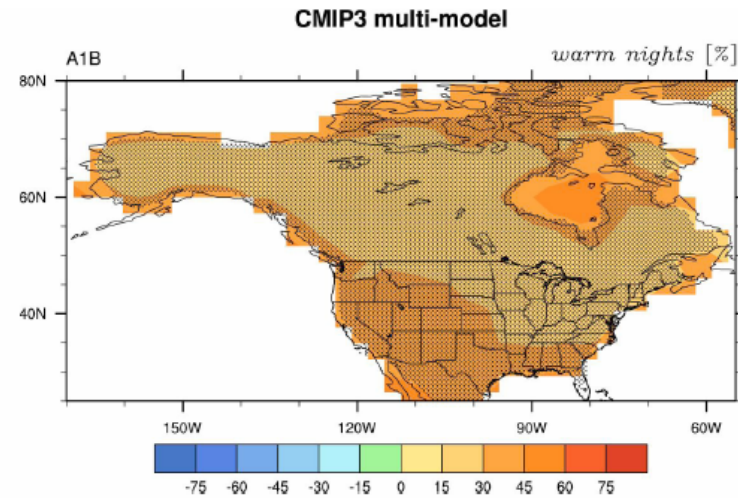
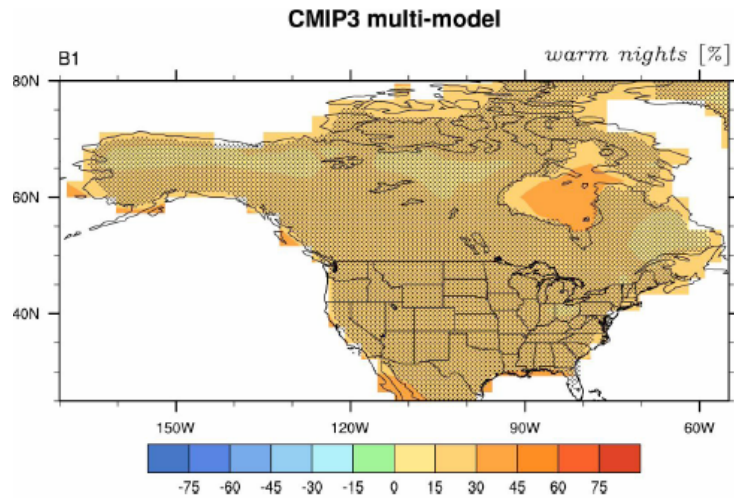
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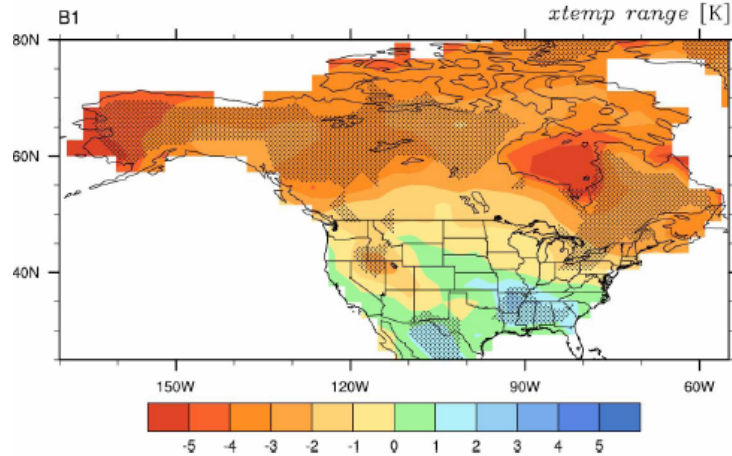


Percentage of warm nights

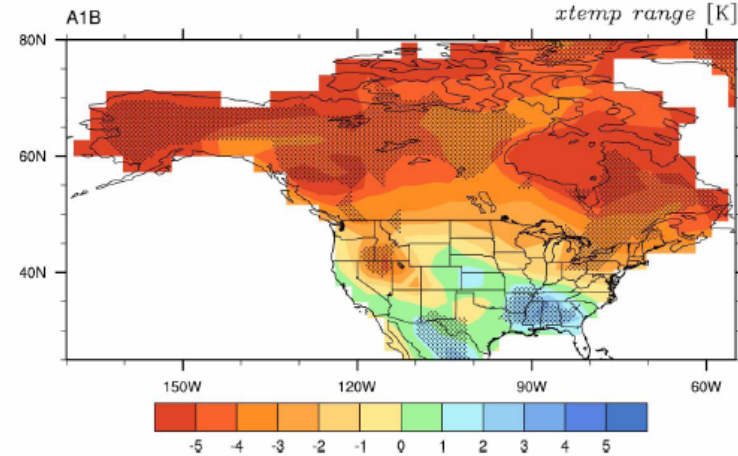


Extreme temperature range

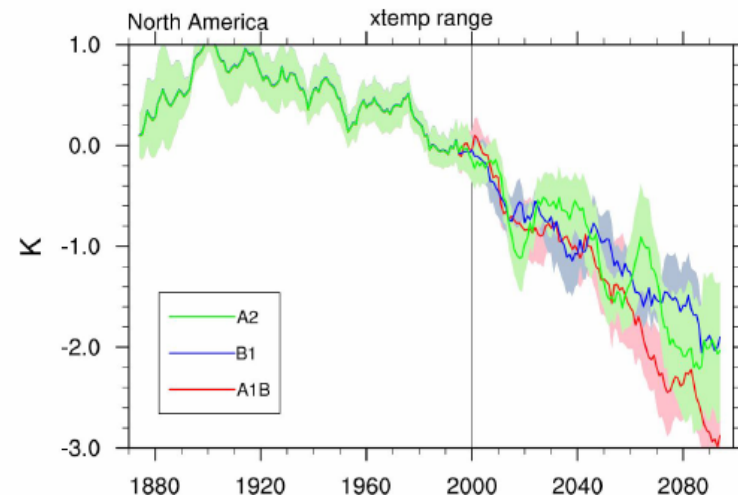
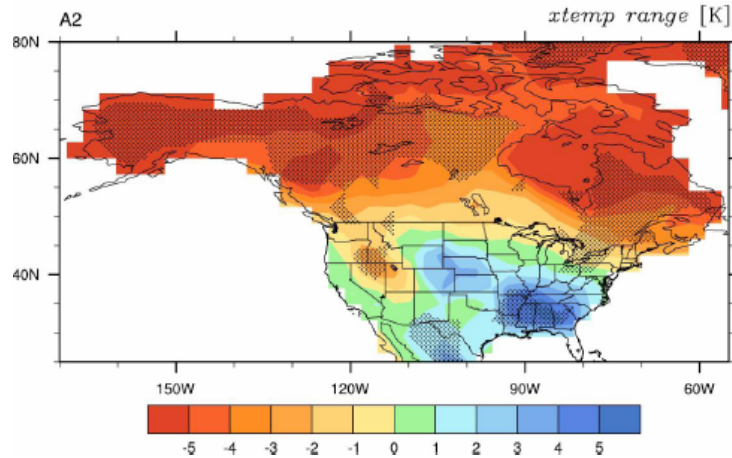
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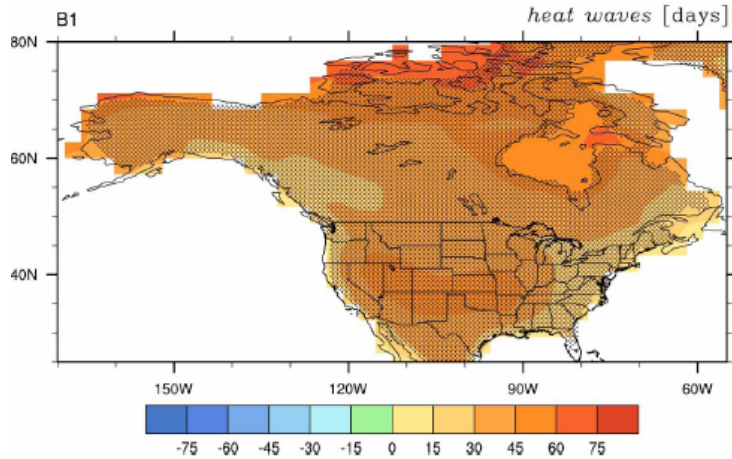


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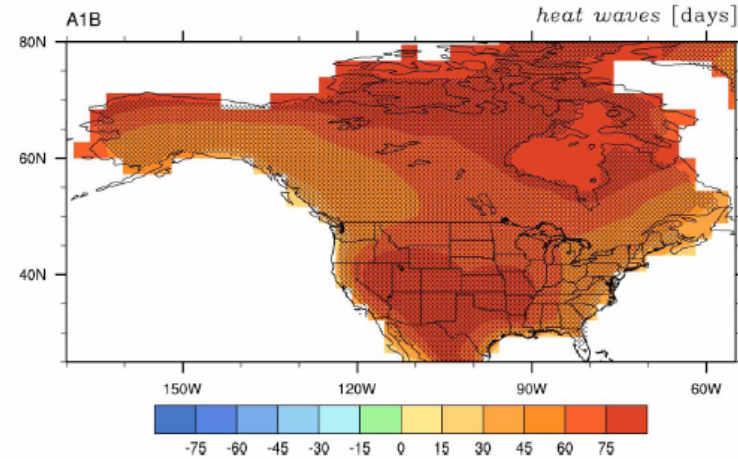


Heat wave duration

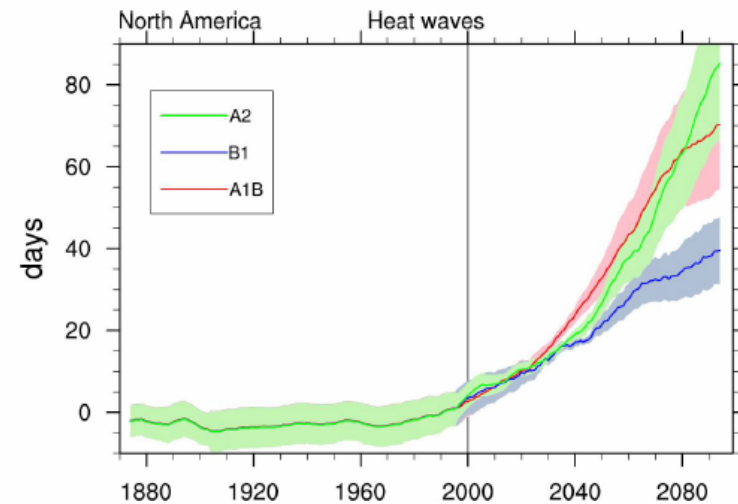
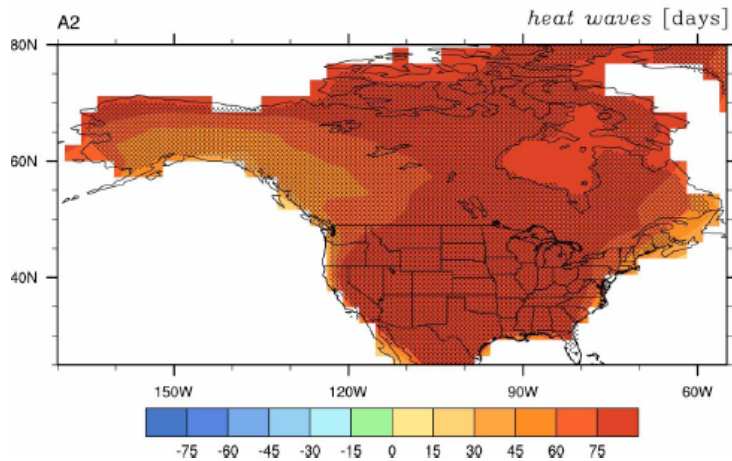
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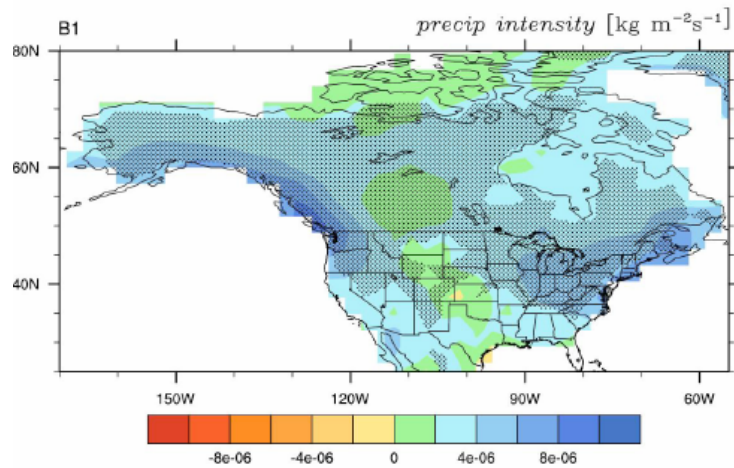


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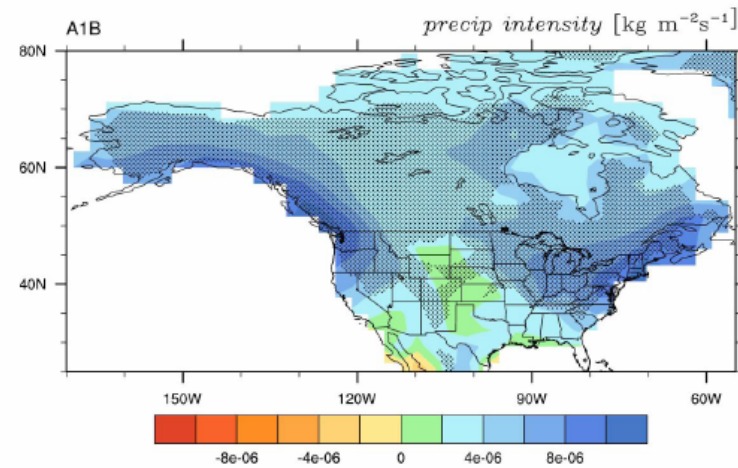


Precipitation intensity

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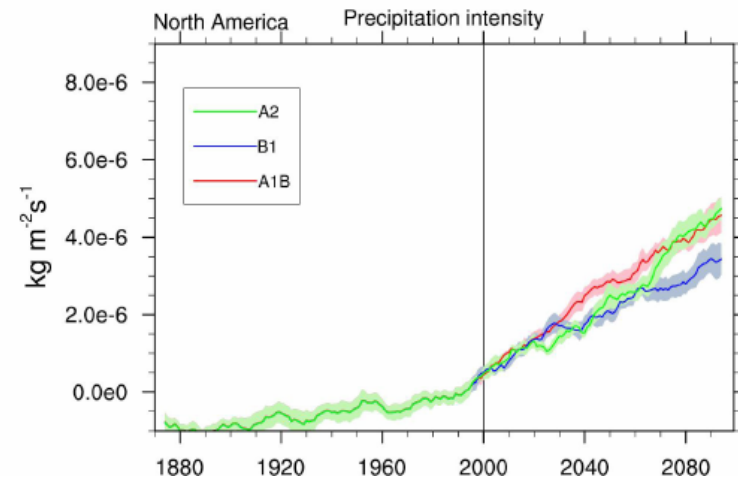
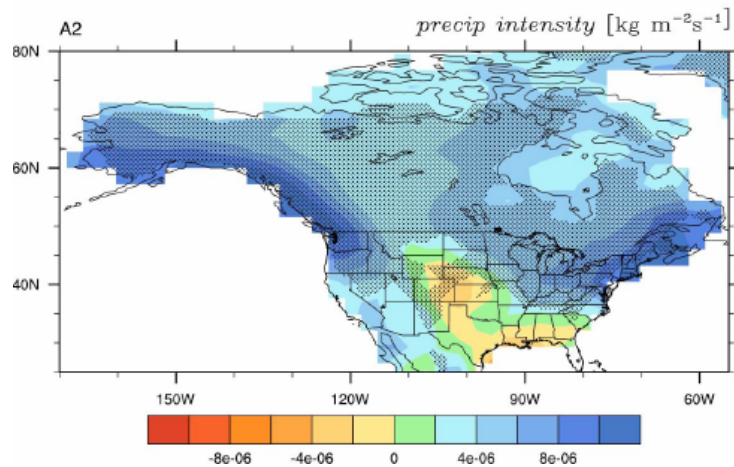


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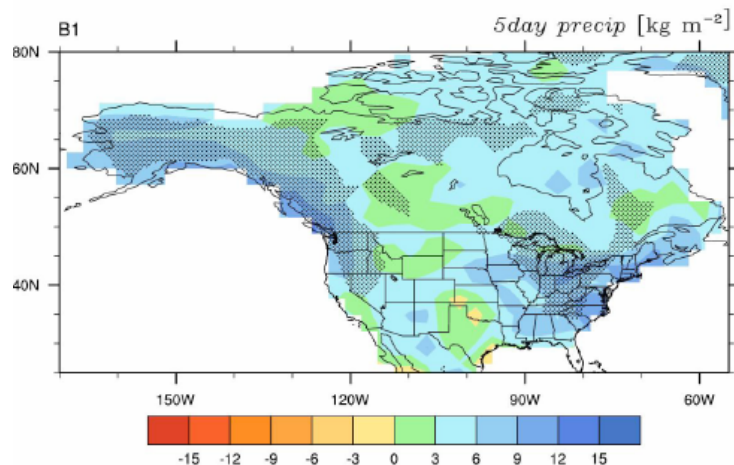
$1.0\text{e-}5 \text{ kg m}^{-2} \text{ s}^{-1} \sim 1 \text{ mm/day}$

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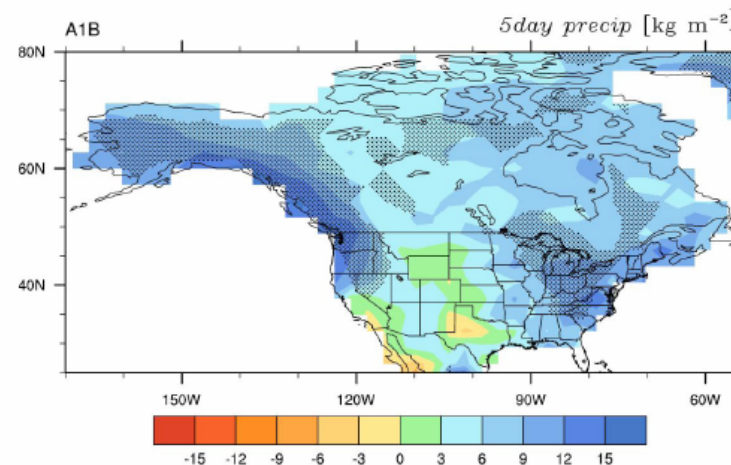


Maximum 5-day precipitation

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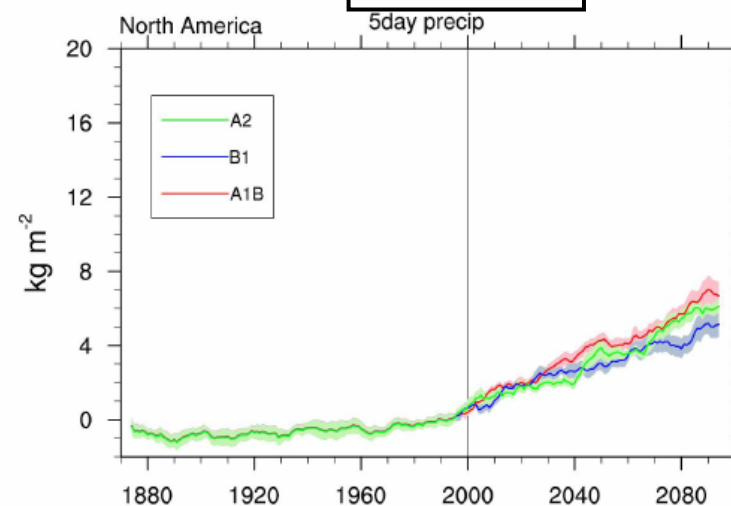
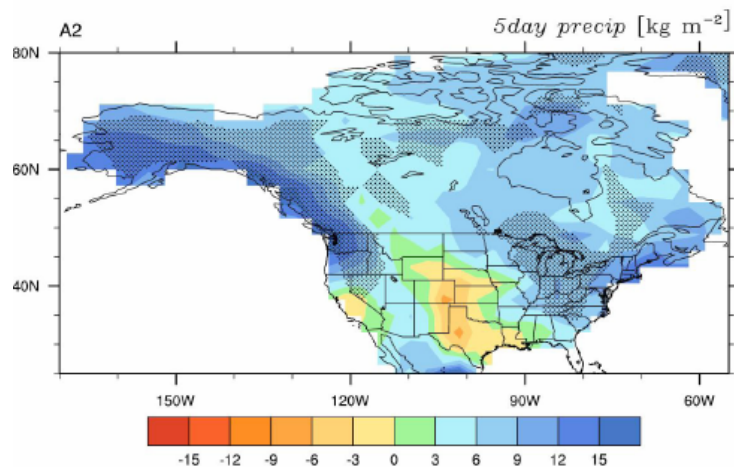


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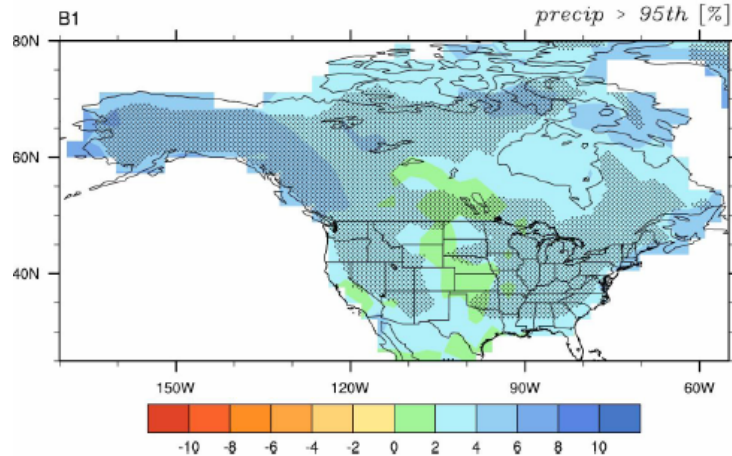
$1 \text{ kg m}^{-2} = 1 \text{ mm}$

CMIP3 multi-model

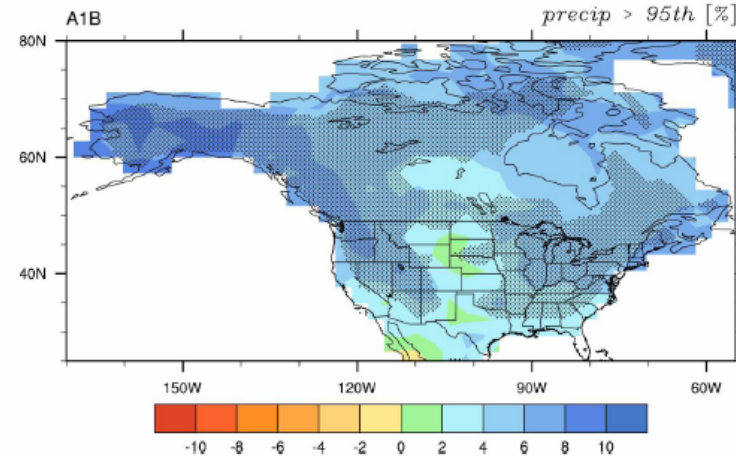


Precipitation fraction > 95th percentile

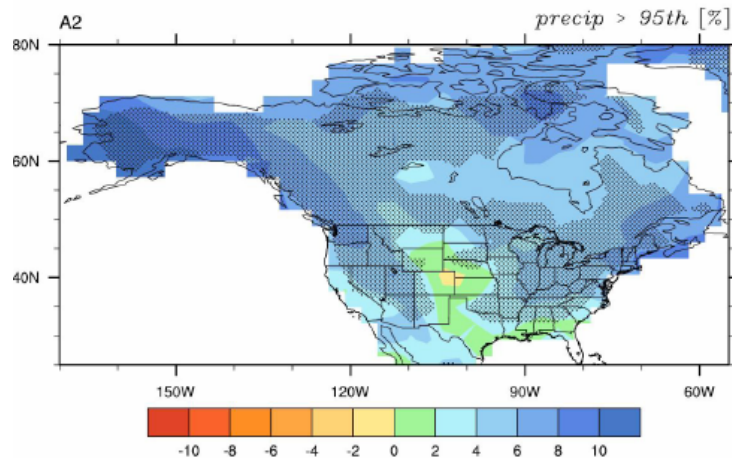
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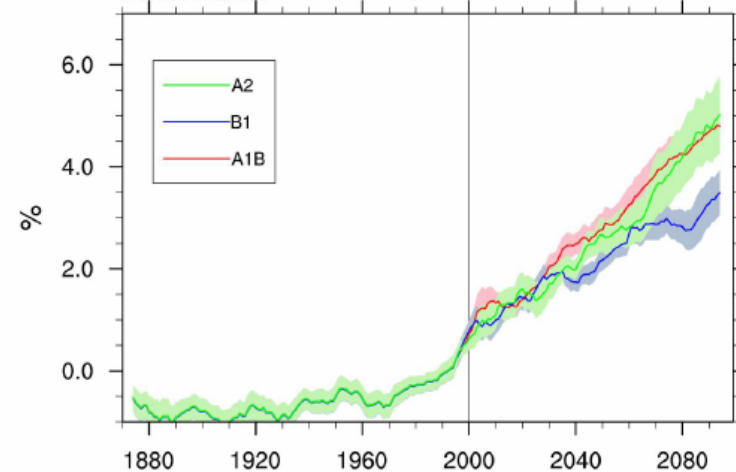
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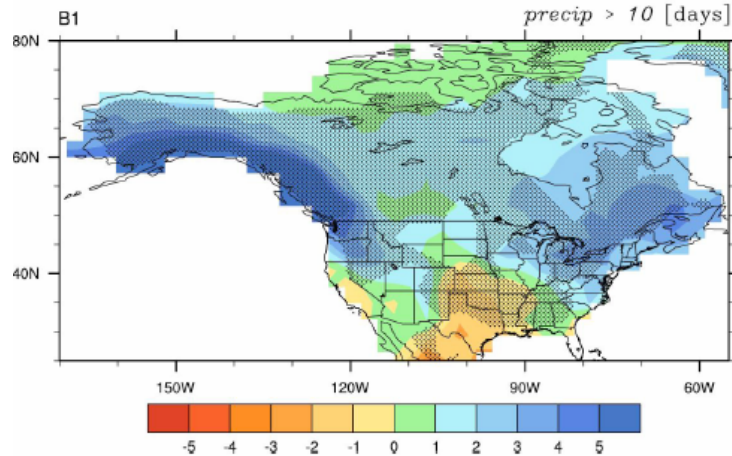


North America *precip > 95th*

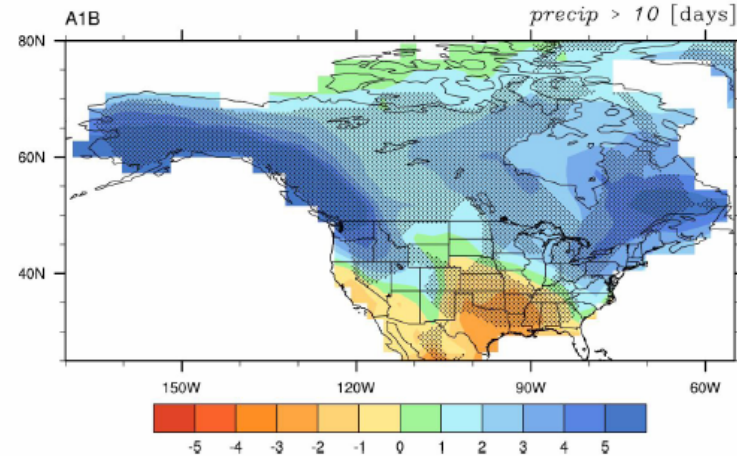


Days with precipitation > 1 cm

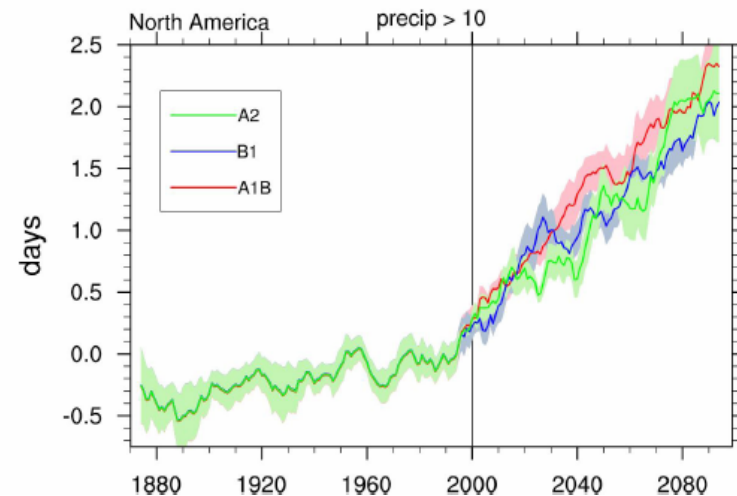
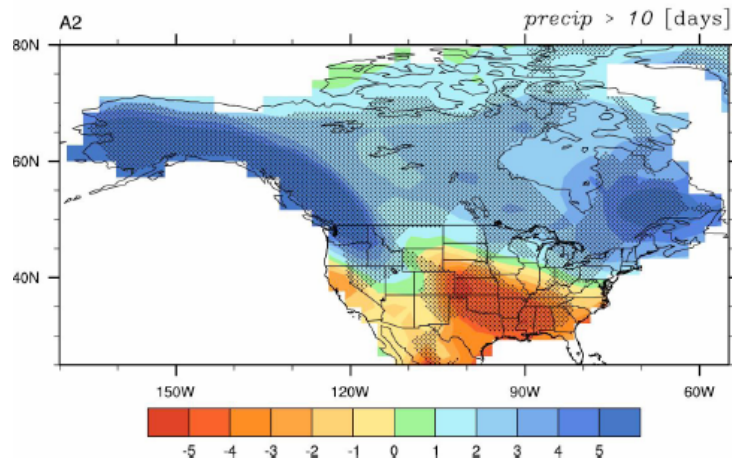
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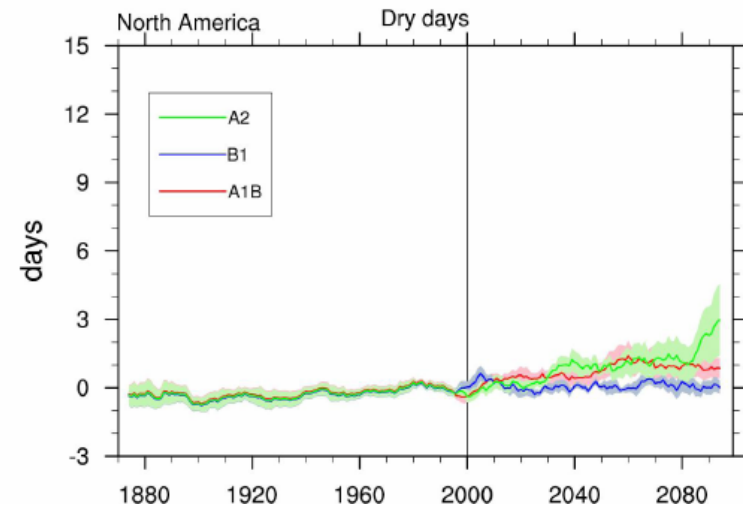
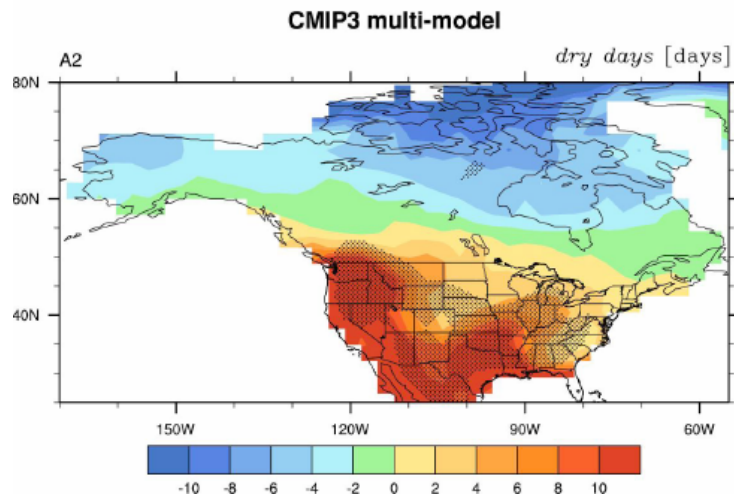
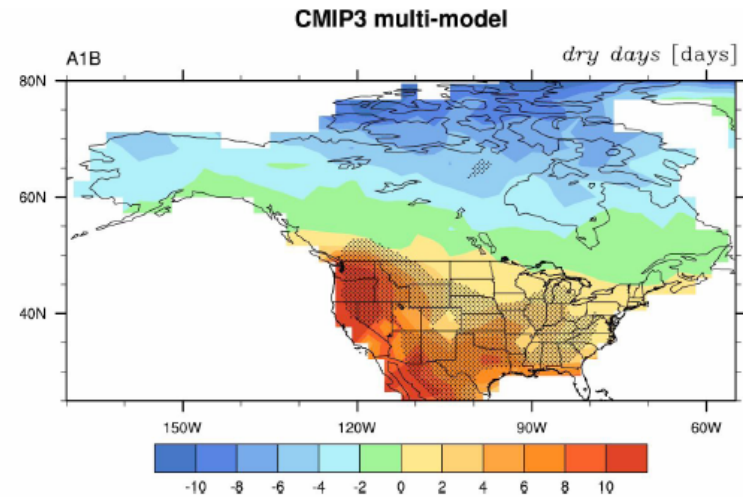
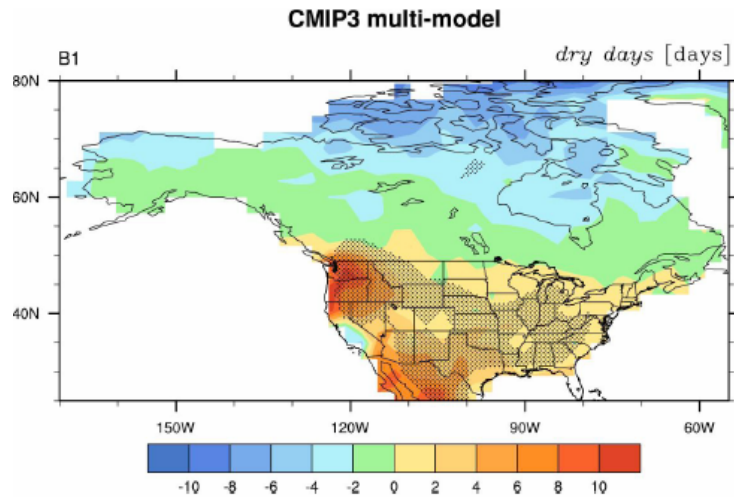
CMIP3 multi-model



CMIP3 multi-model



Maximum number of dry days



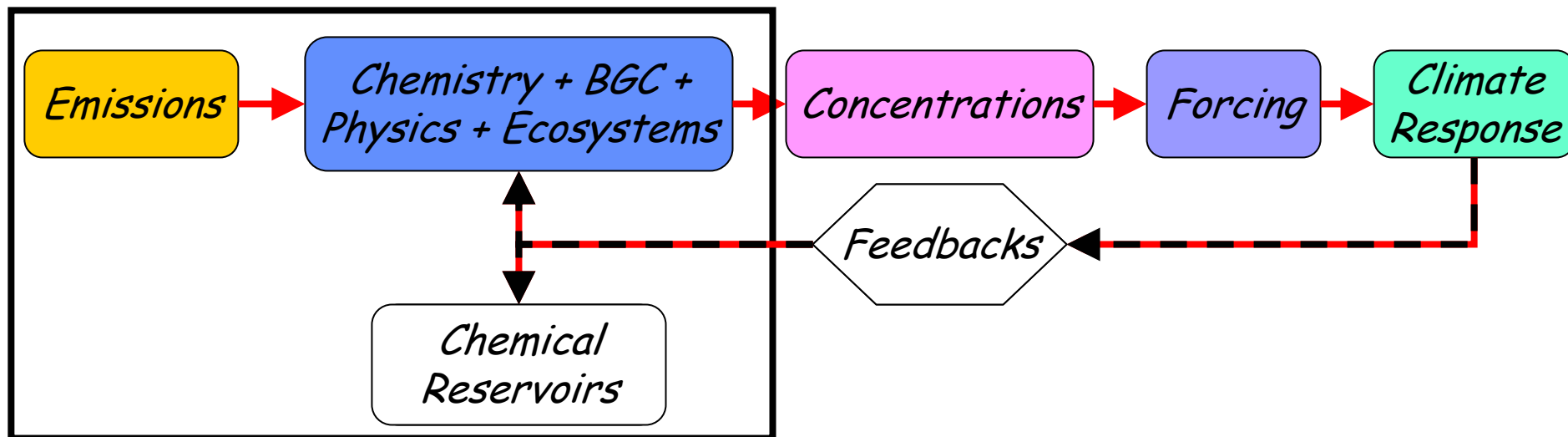
Conclusions regarding extremes



- Longer duration, more intense, and more frequent summer heat waves and hot spells are *very likely*.
- Fewer frost days are *very likely*.
- A reduction in the diurnal temperature range is *likely*.
- Increases in number and duration of dry spells are *likely*.

- The global context of regional climate change
- Climate change in the western regional US
- Changes in climatic extremes in the western US
- Future developments in global climate projections:
 - *Development of Earth system models*
 - *High-resolution models for regional forecasts*
 - *Short-range climate predictions for adaptation*
 - *Coupled climate / policy models*

Simulating the Earth system



- Climate models prescribe the emissions, chemistry, and carbon cycle.
- This approach is simple to implement, but it omits:
 - Chemical and biogeochemical feedbacks.
 - Chemical and biogeochemical reservoirs.
- The next generation of Earth system models will include these interactions.

Advances in global climate modeling: NCAR-DOE CCSM Earth System Model

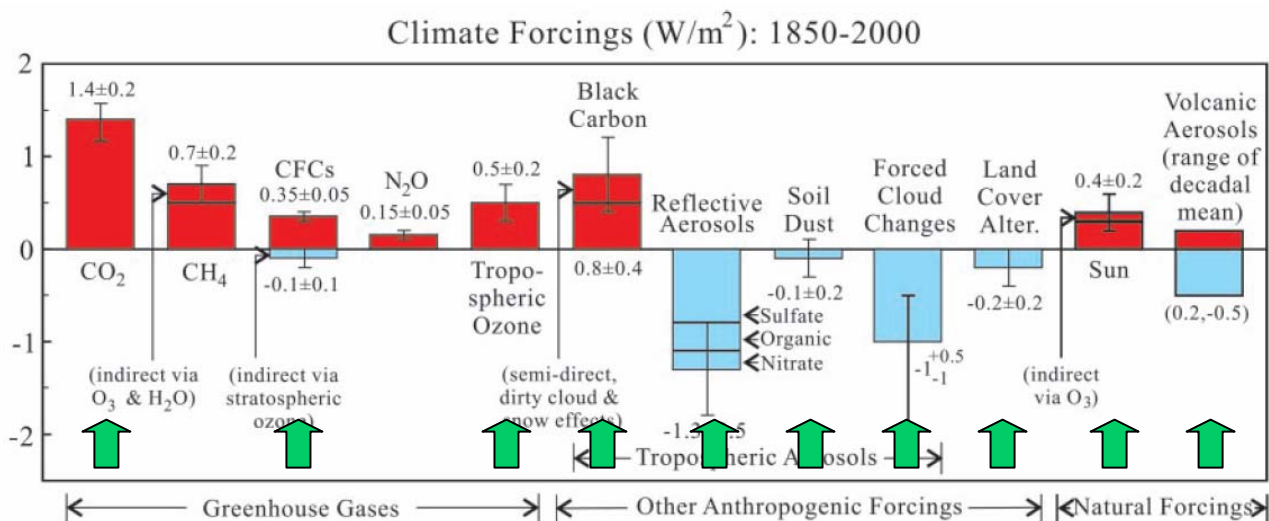
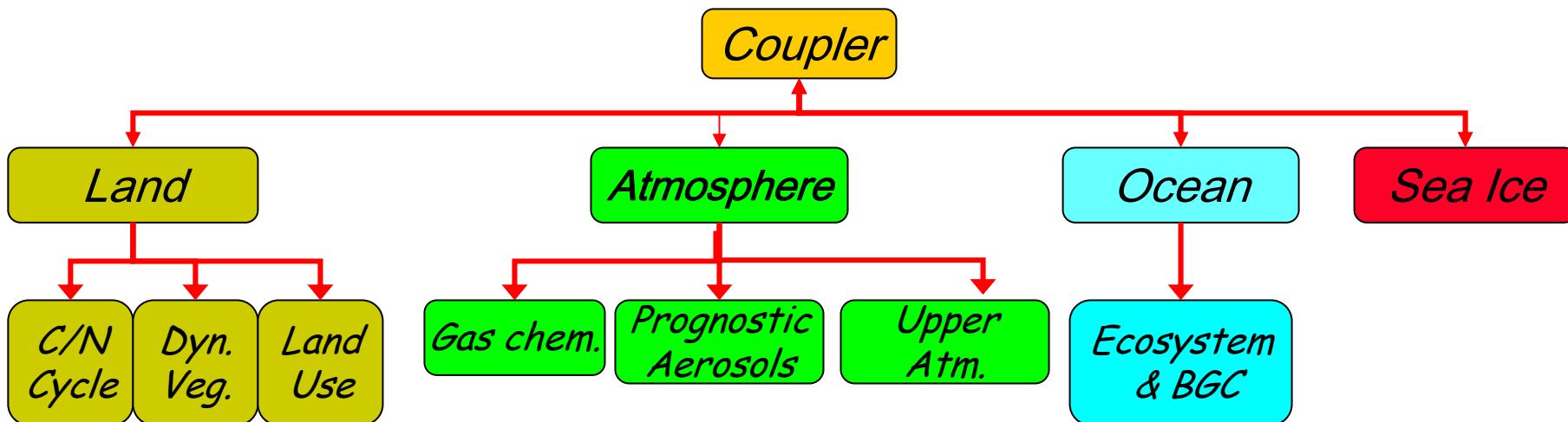
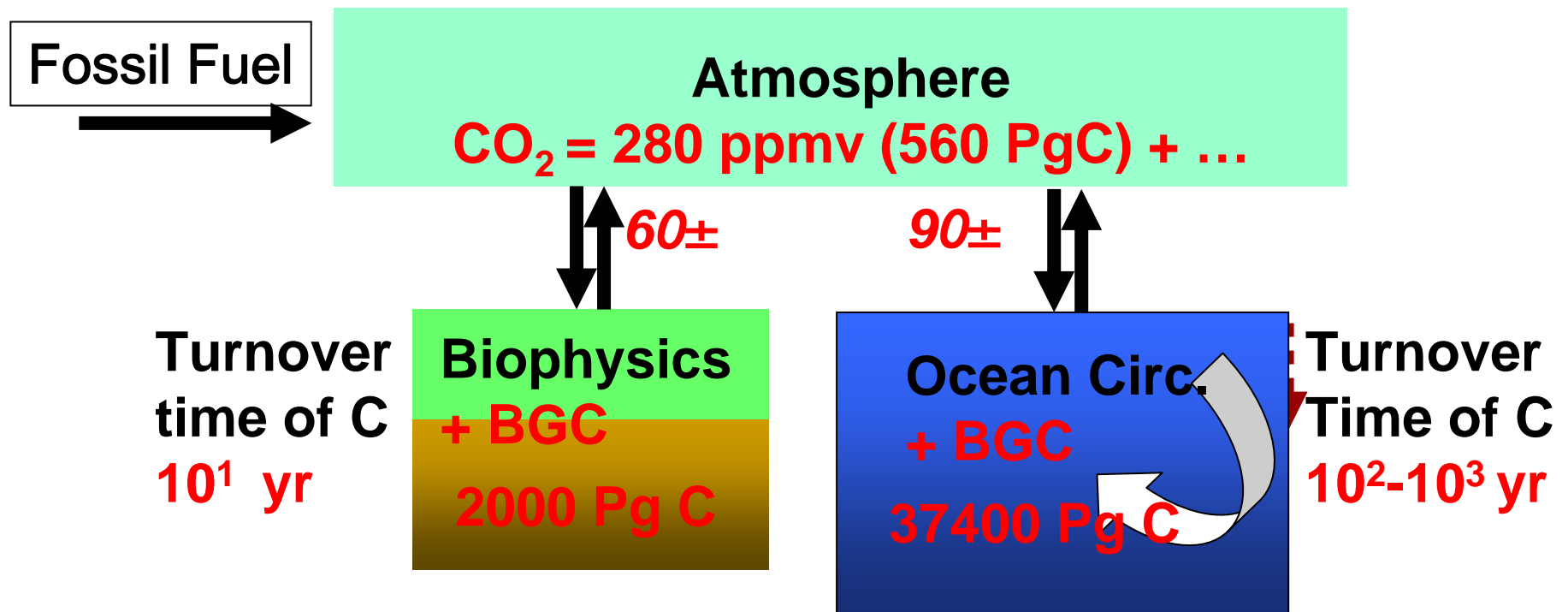


Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.

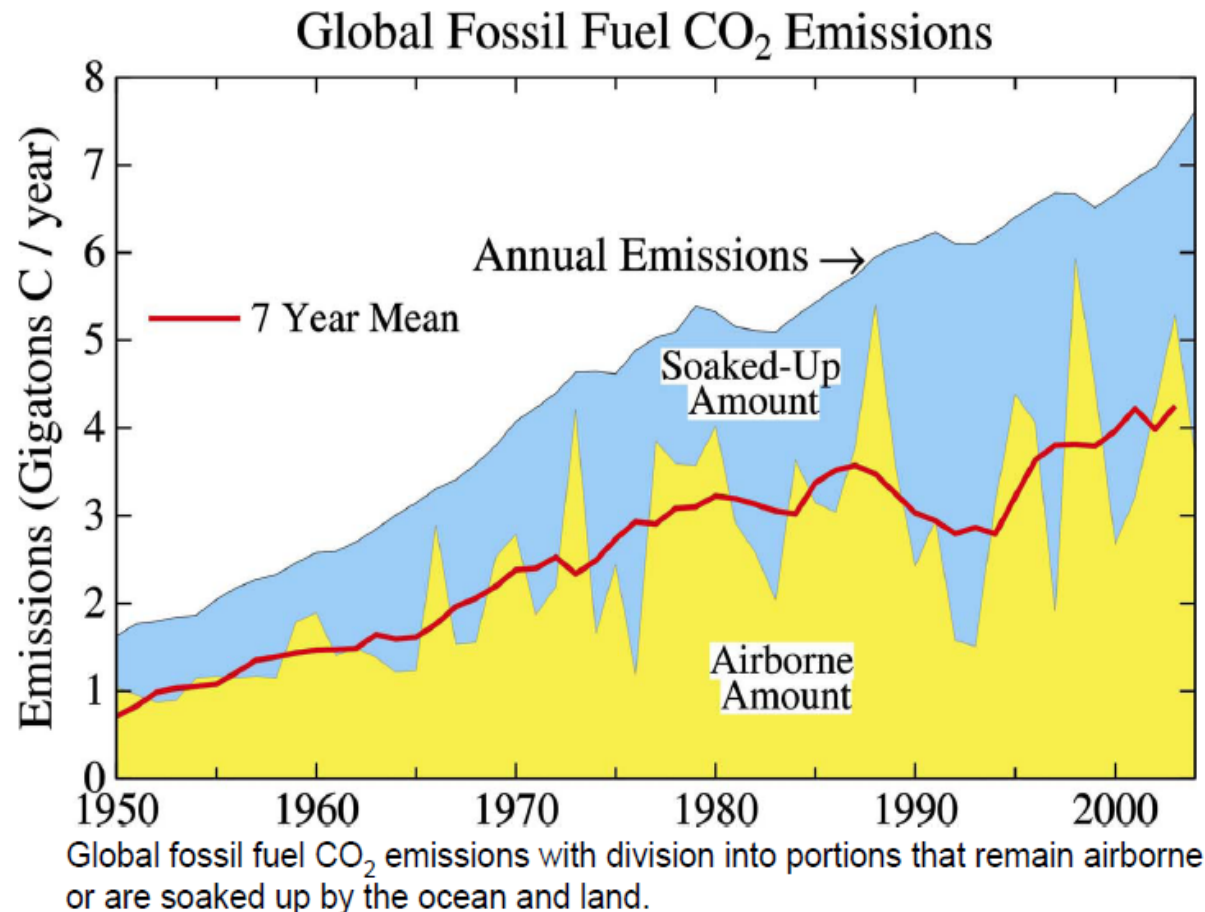
Carbon cycle science:
Will the warming accelerate the warming?



Capacities of land and ocean to store carbon are changing.



- Only half of the CO_2 produced by human activities is remaining in the atmosphere
- Where are the *sinks* that are absorbing over 40% of the CO_2 that we emit?
 - Land or ocean?
 - Eurasia/North America?
- Why does CO_2 buildup vary dramatically with nearly uniform emissions?
- How will CO_2 sinks respond to climate change?



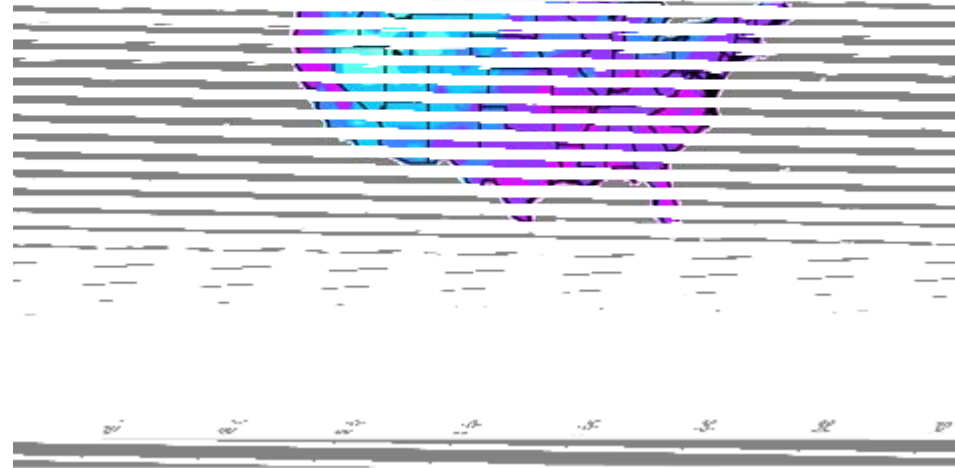
Source: Hansen and Sato, *PNAS*, 101, 16109, 2004.

Higher resolution for precipitation* fidelity

200km

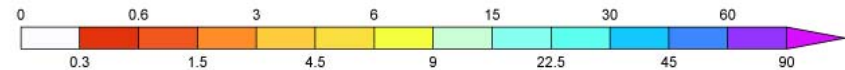
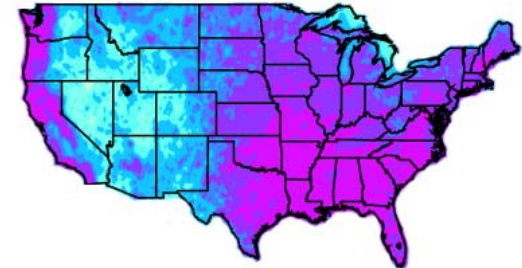
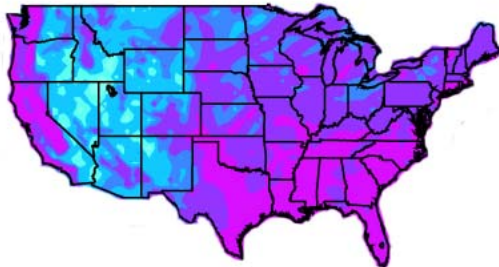


100km



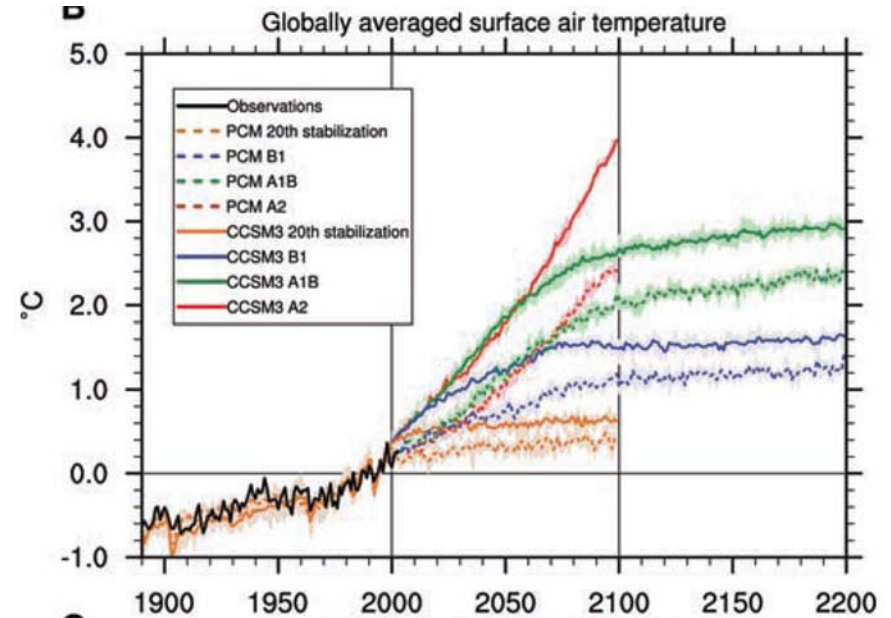
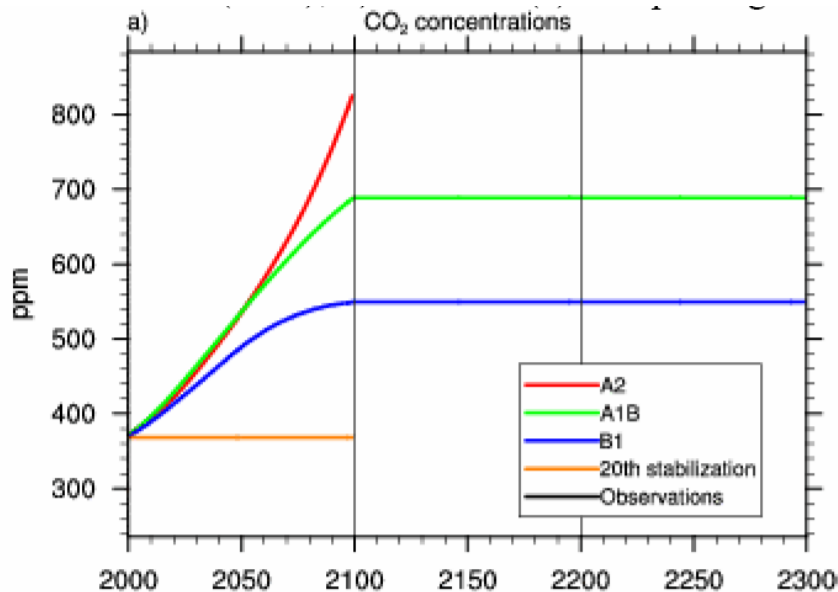
Observations

50km



*20 year annual maximum daily precipitation return value

Convergence of near-term climate forecasts

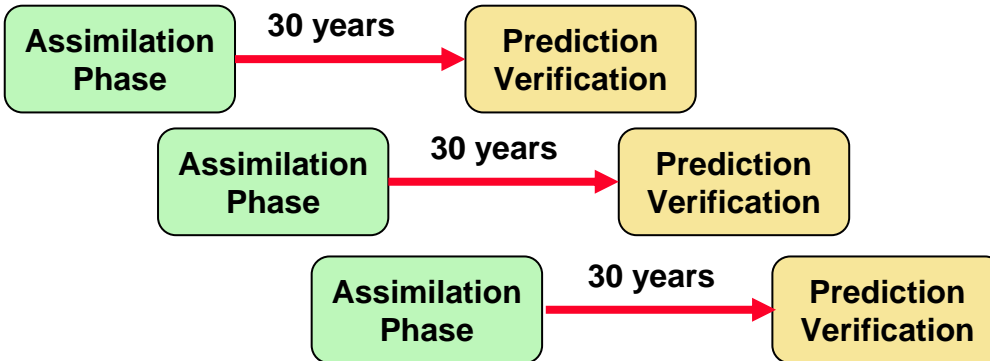


Meehl et al, 2005

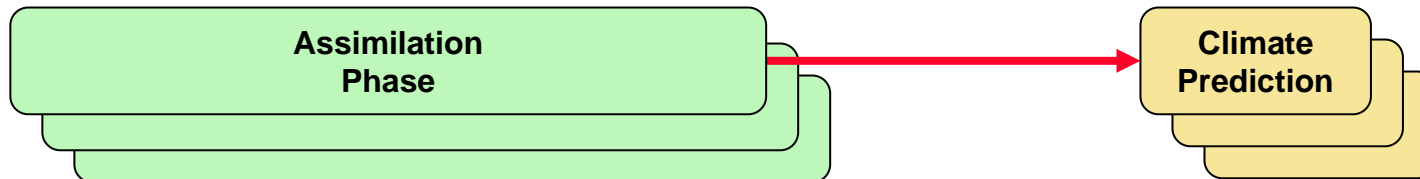
- Between 50 to 70% of warming in 2050 relative to pre-industrial periods is “committed”.
- Therefore the short-range predictions are relatively insensitive to socioeconomic scenarios.

Schema for short-range prediction

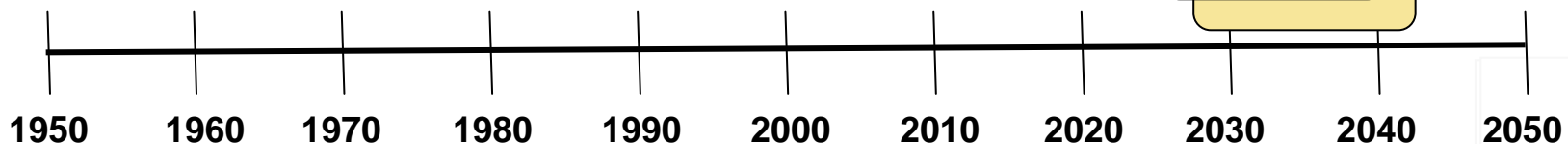
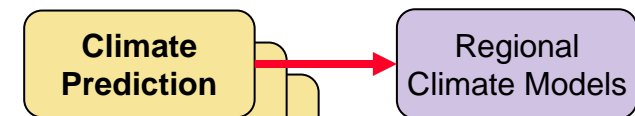
Step 1: Quantify prediction errors using hindcasting



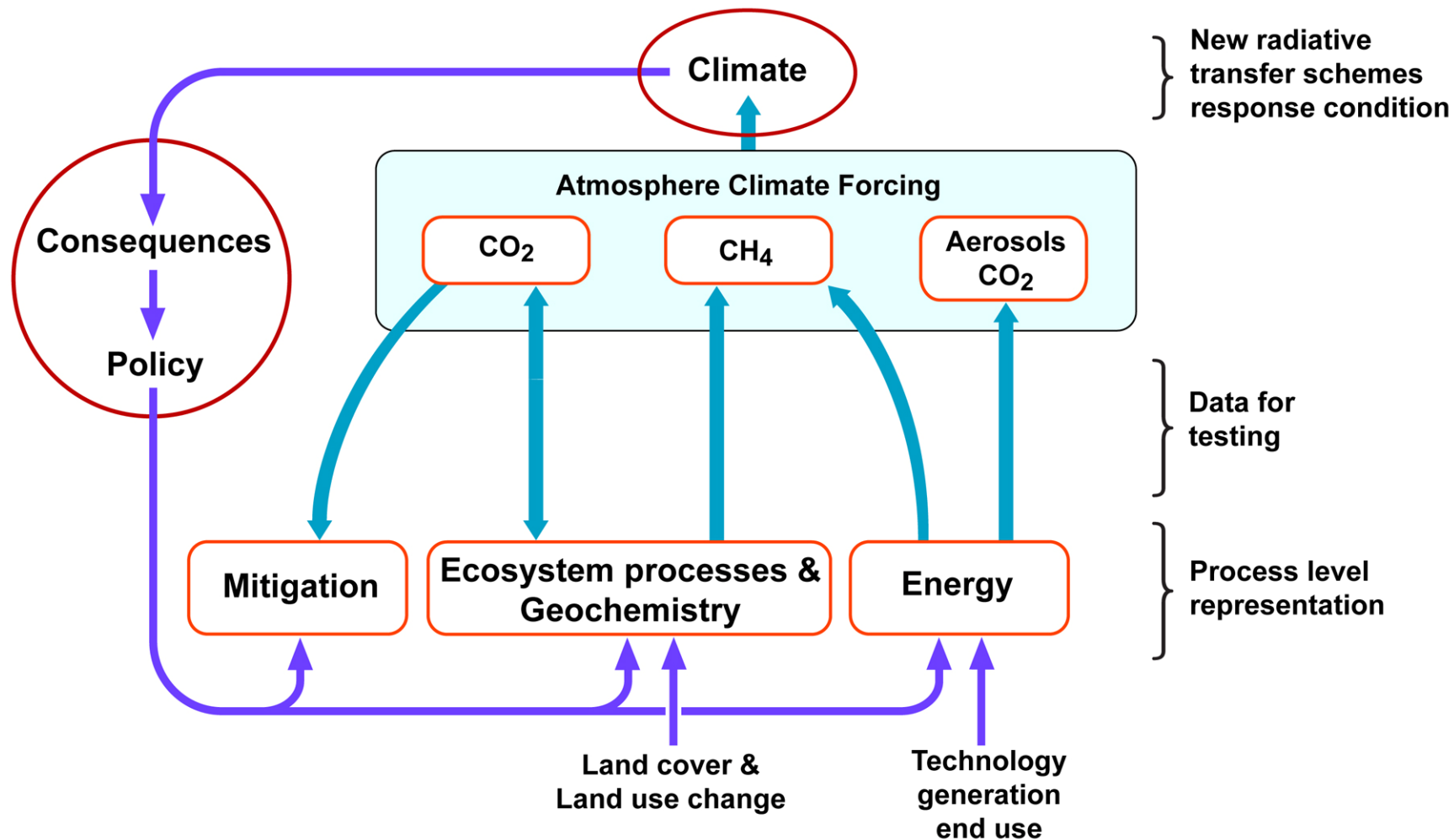
Step 2: Ensemble prediction of near-term climate change



Step 3: Downscaling for regional and national forecasts



Coupled Earth system / policy models



- Recent climate change is very likely human-induced.
- Near-term climate change before 2030:
 - *Western US will be noticeably warmer compared to climatology.*
 - *Predictions converge across models and scenarios.*
 - *This convergence could facilitate process of adaptation.*
- Long-term climate change by 2100:
 - *Extremes include less frost, more dry spells, longer heat waves.*
 - *Warming increases with increasing levels of atmospheric CO₂.*
- There are real prospects for more dynamic coupling of climate modeling, impacts, adaptation, and mitigation.